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GAS AND DUST PROPERTIES IN DWARF IRREGULAR GALAXIES

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Abstract

We present a study of the 158μm [C II] fine structure emission line from a sample of 11 low metallicity irregular galaxies using the NASA Kuiper Airborne Observatory (KAO). Our preliminary results demonstrate that the ratio of the 158μm [C II] emission to the ^{12}CO(1$\rightarrow$0) emission ranges from 6,000 to 46,000. These ratios are significantly enhanced relative to clouds within the Galaxy and to normal metallicity galaxies, which typically have values in the range 2,000 to 6,300. We also find that the [C II] emission in dwarf irregular galaxies can be up to 5% of the far-infrared (FIR) emission, a higher fraction of the FIR than in normal metallicity galaxies. We discuss these results for the dwarf irregular galaxies and compare them to those observed in normal metallicity galaxies. The enhanced 158μm [C II] emission relative to ^{12}CO(1$\rightarrow$0) emission can be understood in terms of the the increased penetration depth of ultraviolet (UV) photons into the clouds in low metallicity environments.

1 Introduction

Low metallicity dwarf irregular galaxies present a new challenge to our understanding of environments where the physical properties of the gas, and the composition and relative abundance of the dust may be very different from those in regions of normal metallicity (*i.e.*, of solar abundance). These galaxies may therefore provide a model for the processes of dust and star formation in the early universe where the metallicities were low. Dwarf irregular galaxies have low observed CO intensities [3] [24] [29] compared to their stellar mass and light, which has often lead to the conclusion that they contain little molecular gas. However, inspite of the lack of large molecular clouds, spiral waves, and bars, dwarf irregular galaxies may produce stars at rates similar to starburst galaxies [8]. The star formation rate in these galaxies, therefore, seems high given the apparent lack of molecular gas. Does this imply that they undergo more efficient star formation, or does the observed CO emission underestimate the mass of the molecular gas in these galaxies? Indeed, the reliability of CO as a tracer of molecular gas has already been questioned both theoretically [14] and observationally [13].

Neutral material at the edges of atomic and molecular clouds is ionised and dissociated by ultraviolet (UV) photons with wavelengths longer than the Lyman limit at 912Å, equivalent to photons of energy $\leq$ 13.6 eV, which originate from nearby O and B stars. Between H II regions associated with the nearby stars and molecular clouds, warm interface regions called photodissociation regions (PDRs) are formed [25]. Carbon, with an ionisation potential of 11.3 eV, is the most abundant element in the interstellar medium with an ionisation potential less than that of atomic hydrogen. The [C II] 158μm $^2P_{3/2}$—$^2P_{1/2}$ far-infrared (FIR) fine structure emission line is the dominant cooling line in low density PDRs ($n_H \lesssim 10^3$ cm^{-3}), in higher density PDRs the [O I] 63μm line becomes an important coolant [25] [26]. The bulk of the UV radiation incident on PDRs is absorbed by dust, and is then re-emitted in the FIR as thermal emission. Thus, the FIR continuum is a measure of the UV radiation field incident upon these regions. The extent of the gas associated with the PDRs in low metallicity dwarf irregular galaxies may be different from normal metallicity PDRs since the UV photons penetrate more deeply into molecular clouds because of the lower relative abundance of dust. The emission from the PDRs in these galaxies will therefore be more prominent, relative to the molecular cores. Thus, mapping the [C II] and CO emission from the interstellar medium in these galaxies can be used to trace the extent of the PDRs relative to the molecular cloud cores.

In this paper we present preliminary results of our [C II] observations for a sample of low metallicity dwarf irregular galaxies, obtained using the Kuiper Airborne Observatory (KAO), and compare them to the results for normal metallicity galaxies.

2 Observations and Results

We have observed the 158μm $^2P_{3/2}$–$^2P_{1/2}$ far-infrared line emission of [C II] in the following dwarf irregular galaxies using the FIR Imaging Fabry-Perot Interferometer (FIFI) [18] [23] and Cooled Grating Spectrometer (CGS) [5] [6] [7] on the KAO: NGC2366, NGC3077, NGC3738, NGC4214, IIZw40 and He2-10. Additionally, in our sample, we include the published data on IC10 [13], NGC6822 [10], 30 Doradus in the Large Magellanic Cloud (LMC) [19], and NGC1569 and NGC4449 [12]. The metallicities, expressed as O/H, range from 0.1 to 0.8 of solar abundance in this sample of dwarf irregular galaxies

In trying to understand the relationship between the [C II] and CO emission, and hence the usefulness of CO as a tracer of molecular gas, we consider the ratio of the integrated intensities of [C II] to ^{12}CO (1$\rightarrow$0) emission, and the ratio of the [C II] emission to FIR continuum in this galaxy sample. The $I_{[CII]}/I_{CO}$ ratio can be used as a measure of the PDR emission relative to molecular core, and $I_{[CII]}$/FIR is a measure of the fraction of the incident UV energy that re-emerges in the [C II] cooling line. The CO data are taken from the literature [2] [3] [4] [17] [21] [24] [27]. From a previous study of normal metallicity galaxies [23], it was shown that $I_{[CII]}/I_{CO}$ is indicative of the degree of star formation activity. For example, quiescent non-starforming galaxies and Galactic regions have $I_{[CII]}/I_{CO}$ of order 2000, and in more active galaxies and Galactic starforming regions this ratio is about a factor of three higher (6300 [23]). For our sample of dwarf irregular galaxies we find values of this ratio ranging from 6,000 to 46,000, with a median value of 16,000. The ratio of the $I_{[CII]}$ to FIR continuum, defined as the sum of the Infrared Astronomical Observatory (IRAS) 60μm and 100μm bands, is generally less that 1% for solar metallicity galaxies. In our sample we find values of this ratio as high as 5%.

3 Discussion

The above observations and results can be understood in terms of the low metallicity effects in these galaxies [14]. The effects are primarily a result of the reduced abundance of the dust relative to the gas. The dust in a cloud determines the penetration depth of the UV photons and hence the extent of the PDRs. In a normal metallicity cloud the UV photons penetrate to a depth equivalent to a few A_V [25], which corresponds to a thin PDR shell, from which the [C II] emission is seen, around a large molecular core [25]. The CO is protected in the cloud core where A_V is greater than a few. However, in the low metallicity case, the UV photons still penetrate to a depth equivalent to a few A_V, but because of the lower dust abundance the associated PDR now extends much deeper into the cloud giving rise to a much reduced molecular core where the CO is to be found [15]. In the normal and low metallicity cases the [C II] column density is about the same, because the dust and the [C II] abundances are both proportional to the metallicity. Hence, $I_{[CII]}/I_{CO}$ is enhanced in the low metallicity environment because the [C II] and CO have very different filling factors from each other. A similar conclusion was reached for the emission from the 30 Doradus region [19] and the N159 and N160 complexes [9] in the LMC.

The case of molecular hydrogen is, however, somewhat different because H_2 self-shields more efficiently than CO. Models of individual clouds of varying metallicity [14] [28] [15] demonstrate that, indeed, the [C II]-emitting zone can harbour self-shielded H_2. Thus, there can be a substantial reservoir of molecular hydrogen in these systems that is not traced by CO observations. This raises interesting questions about the actual gas inventory in low metallicity systems. Measurements of the molecular mass in low metallicity galaxies based on the observed CO emission alone can therefore underestimate the total molecular mass in these objects. Observations of [C II] provide evidence for a large hidden reservoir of H_2 in the low metallicity galaxy IC10 [13], where it has been speculated that up to one hundred times more molecular hydrogen is present than has been estimated from the ^{12}CO (1$\rightarrow$0) observations.

In our sample of galaxies, the higher $I_{[CII]}/FIR$ ratios, compared to normal metallicity galaxies, may also be a result of the low metallicity, but the exact cause of this effect is not well-determined. The [C II] emission is a measure of the cooling of the gas, which is primarily heated by photoelectron emission from the smallest particles in the local dust size distribution, according to a recent model [1]. In this model these small particles are assumed to be polycyclic aromatic hydrocarbon molecules (PAHs) and carbon grains containing up to a few thousand atoms. Thus, the [C II] emission depends on the relative abundances of the carbon in the gas phase and in the PAHs and small grains. However, the FIR continuum emission arises from the absorption of the radiation field by much larger particles. If indeed PAHs and small grains dominate the heating of the gas through photelectron emission [1], then the [C II] emission should be a measure of the total PAH and small grain cross-section. The FIR is then a measure of the total cross-section of the large grains. It has been suggested that the origin of the higher $I_{[CII]}/FIR$ ratio is due to a dilution of the ambient far-ultraviolet (FUV) flux because the mean free path length of the photons is increased in low metallicity clouds [9]. However, it might be expected that such a dilution of the FUV flux absorbed by the dust would equally effect the resultant photoelectron emission from PAHs and small grains, and the absorption by the large grains. In general, one could interpret the high $I_{[CII]}/FIR$ ratio as implying that the total cross-section of the PAHs and small grains, relative to the large grains, increases as the metallicity decreases. This is consistent with the enhanced UV and FUV extinction, relative to the optical, seen in the Large and Small Magellanic Clouds [11] [16] [20]. One would therefore expect that the emission in the IRAS 12μm band, due to thermal emission from PAHs, should increase relative to the FIR as the metallicity decreases. However, completely the opposite effect is observed [22]. For our sample we find the same trend as [22] for the ratios of the IRAS 12μm to 100μm and for the 25μm to 100μm bands, as a function of metallicity. The exclusion of the 60μm band, in these cases, removes any contribution from warm intermediate-sized grains to the FIR continuum. It is interesting to note that in our sample neither the IRAS 12μm or 25μm bands correlate with the [C II] emission, and this seems counter to the basic idea that the PDR gas is heated, primarily, by photoelectrons emitted from PAHs and small grains [1].

In low metallicity clouds it is possible that the heating of the gas through the FUV pumping, and then collisional de-excitation, of vibrationally excited H_2 is enhanced relative to the photoelectron heating from the PAHs and small grains. However, this source of gas heating only contributes of order 1% of the total heating [25], and is unlikely to be sufficiently enhanced for the metallicities typical of our galaxy sample ($0.1 < O/H < 0.8$).

Thus, we find that our observations of dwarf irregular galaxies do indeed present new challenges to our understanding of low metallicity environments. Clearly, detailed modelling of low metallicity molecular clouds is required in order to understand the enhanced $I_{[CII]}/I_{CO}$ and $I_{[CII]}$/FIR ratios in these galaxies.

4 Conclusions

In normal metallicity galaxies the [C II] 158μm cooling line has an intensity < 1% of that of the total FIR continuum, which is a measure of the intensity of the radiation field. In this sample of 11 low metallicity dwarf irregular galaxies we find values of this ratio of 0.5–5%. We also find $I_{[CII]}/I_{CO}$ ratios ranging from 6,000 to 46,000 which are enhanced compared to normal metallicity galaxies. These results clearly indicate differences in the PDR and molecular core properties as a result of the reduced metallicity. In low metalliciy regions the UV photons penetrate deeper into the cloud, than in the normal metallicity case, resulting in an increased [C II] emitting zone and a reduced CO core. These effects are the origin of the higher $I_{[CII]}/I_{CO}$ ratios that we see in our dwarf irregular galaxy sample. In addition we find that the ratios of $I_{[CII]}$/FIR are higher in our sample than in normal metallicity galaxies. The origin of this enhancement is not yet explained by the available molecular cloud and PDR models. Observations of [C II] and CO, taken together, will probably provide a more reasonable estimate of the total molecular mass inventory in low metallicity galaxies. We conclude that in order to better understand the origins of the enhanced $I_{[CII]}/I_{CO}$ and $I_{[CII]}$/FIR ratios in these galaxies, new models of low metallicity molecular clouds are required.

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